I. Introduction

Is there some fundamental limitation that explains the apparent large spread of performance for C/M

We were charged in essence with the problem "Is something wrong with C/M and if so, what?"

The first step in coming to grips with this question is to agree to methods for evaluating the system. Since the end result is a photographic image we must construct an objective quantitative measure of image quality. Against this standard the performance of the system must be measured and the observed image ~~is to be~~ compared with the one to which the system is designed - including effects of atmosphere, image motion and film processing and sensitivity in addition to the lens system.

If all of these factors are fully understood and the design performance is achieved, then we conclude C/M is a satisfactory system in the sense we have given it a test and it has passed. There is a big question of course, have we given the right test, i.e., the most useful one from the viewpoint of the mission we want C/M to accomplish. In more specific terms we speak of the optical transfer function or the sine wave response curve t (k) as a function of spatial frequency k as the most convenient meeting ground between design and performance. In the engineering design of an optical system one seeks maximum resolution in lines/mm by keeping t (k) as large as possible in the region of high k. spatial frequency

It is the primary concern of this Committee to determine to what extent the design t (k) is achieved by the system in practice. On the other hand, there are users criteria of quality and ~~it is not clear that one~~ one might ~~not~~ benefit ~~when it comes to realizing the maximum intelligence or~~

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~~reconnaissance value of the pho~~tography by trading off some resolution ~~in~~ for system contrast order to achieve a certain percentage gain of density difference Δ D for the image - this is a human factor involving the PI's.

~~B.~~ This question of the optimum design of a transfer function for the intelligence community is a corollary and vital problem ~~but is of secondary importance to this Committee.~~

The first section of our report is devoted to this question of constructing an objective measure of image quality that is both useful and experimentally feasible.

In practice, in the real world, there are many parameters affecting the performance which cannot be precisely specified. The transfer function, t (k), is a product of four components

$$t\,(k) = t\,(k)_{\text{atmosphere}}\; t\,(k)_{\text{image motion}}\; t\,(k)_{\text{optics}}\; t\,(k)_{\text{film}},$$

and uncertainties in these individual factors make it impossible for us to say that the system passes any test perfectly. (We also recognize that this characterization of performance by t (k) is incomplete since granularity is not taken into account. In these discussions we assume the slow very fine grained film 4404 now in use is a fixed parameter of the system.) Rather we must content ourselves by reporting it to perform within a certain quality range. The more we can sharpen up the individual factors the more precise will be our understanding of the system. This calls for a Measurement Program which is the subject of Section II of our report. Engineering passes over known design targets in known weather conditions are one aspect. Another very important one is an in-flight measurement program to determine what the effect of the in-flight environment is on the optical focus - one area of particular

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concern being the possible focal ~~freak~~ errors introduced by thermal gradients and transients in the camera barrel and lens system. We do not here attempt a detailed design study but we indicate the types of measurements felt to be most desirable and which can be made on ground or in orbit without substantially conflicting with the operational goals of the C/M missions.

As a general remark we add our very strong conviction of the need for instituting with great urgency a program of mission measurements and analyses to help identify the causes degrading most of the image quality obtained so far - or to verify by establishing a lack of correlation between the image quality and the monitored parameters that the present quality is typical of what is to be expected.

In view of the extremely limited technical feedback as to the performance of components in flight to the systems designers, it is amazing to those of us on the "outside" how well C/M has done so far. Nevertheless there are major performance variations that understood ~~It is clearly not yet a production system in that failures when they occur~~ follow no ~~set~~ pattern from one mission to the next. ~~and seem to involve different components~~. In its best moments it has performed very well, indeed, ~~amazingly~~ in view of its complexity, indicating that improvements to a higher level of reliability should be possible. The urgency of a measurement program and of timely systematic performance analyses as required by the designers in order to achieve such improvements cannot, therefore, be overemphasized in this report!

II. Outline

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OUTLINE OF REPORT

I. Objective Measures of Image Quality

A. <u>Discussion of edge measurement techniques for determining the optical transfer function</u>.

The aim here is to provide a reliable and reproducible "canonical" technique for accurately measuring t (k) particularly for high spatial frequencies. We want to know t (k) for two reasons. By comparing the measured t (k) with the value to which the system is designed we can hope to answer whether the photography obtained (say 15 ft ground resolution or 75 l/mm) is all that we can expect from C/M or whether there is a loss of resolution due to shortcomings of the system. Since the atmosphere's transfer function enters into this comparison it too must be measured or calculated as part of a measurement program. This is discussed further in Section IV. A second major reason for finding t (k) is to determine the trade off between resolution, say in l/mm, vs film graininess, vs contrast measured by $D_{max} - D_{min}$ when it comes to optimizing a system with regard to the users' ability to gain intelligence value from the photography.

The practicability of edge measurements for a routine evaluation of photography at high resolution must still be established. Experiments are in progress, further ones are proposed, and the institution of an unclassified professional study for standardization of ~~canonical~~ edges and edge scan techniques to demonstrate practicability of this method for high resolution analysis is recommended.

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B. <u>Visual Comparison of Photography of Unknown Quality With Photography of Known Quality as Obtained by the Same Optical System</u>.

This technique of ~~photographic KEYS~~ subjective quality comparators or JEMS for judging image quality is of great importance because there are no standard resolution targets in operational photography and the edge scan measurements are still ~~of uncertain merit~~ under study. Moreover comparative analysis of properly prepared Keys or Jems will provide some valuable input into a human equation for the optimum photography for use of the intelligence community.

The first use of such photographic comparison keys is for engineering evaluation. They are designed to permit the observer to identify the main specific causes of performance degradation in the actual picture - be it reduction of the optical transfer due to focal errors, nm-optimal processing to high or low average densities, or uncompensated image motion - by comparison with a library series of JEMS that can be brought to adjacent positions in sequence. The second use would be to determine the effects of the variables introduced into the keys or Jems on the value of photographic material for intelligence purposes. To reiterate an earlier point - our primary committee concern is to determine how well the system produces its design transfer function but the question of what transfer function to which the system is to be optimally designed is a corollary and not a separate question.

A comparison technique for assessing the photographic quality is presented and the basic elements of a key or Jem library are discussed here. As the first step in implementing this program a simple dual

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microscope system and a small library with Jems of varying resolutions and contrasts has been prepared.

One specific datum to be hoped for from a comparison of visual photography with JEMS is a correlation with other subjective measures of image quality, such as the MIP ratings at NPIC and the RES measures at SPPL, and with results of standard 3-bar target measurements. We have found an apparently complete absence of correlation between MIP and RES ratings and it remains to establish what quantitative value if any can be placed on the one or the other. In this connection we would like to place in proper perspective the performance curve plotted by Dirks and Maxey on Mission 9056 which has caused such very great concern and which helped stimulate the formation of this committee. In view of our present lack of any objective quantitative measure of image quality it is unknown how either to scale or normalize the MIP values with resolution in lines/mm or in ft resolved on the ground and therefore no conclusions based on such comparison are validly to be inferred.

II. Measurement Program

A. <u>In Flight Measurements for Obtaining Engineering Data to Check on System Performance in the Operational Environment and to Correlate with Image Quality</u>.

The C/M system is subjected to extensive laboratory tests on the ground in [redacted] check its operation both before and after thermal and pressure changes, in different gravity orientations, and after severe vibrations. These tests are designed

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to cover the range of parameters anticipated during launch and orbital phases and null effects on the focal settings are established within rigid tolerance.

There is no way of knowing, however, that serious focal errors do not degrade actual system performance in flight resulting from thermal gradients and transients since no in-flight measurement program exists for determining the temperature inhomogeneities in flight due to sun angles and camera barrel exposure to space and furthermore no in-flight verification that the focal point is at the film platten is made. Remedies for these deficiencies are proposed. They require an in-flight measurement program involving only one of the two C/M cameras but not seriously interfering with its operational activities. Furthermore, a vigorous and more thorough laboratory study with a theoretical model is encouraged to complement this program, providing more details as to where to put temperature sensors on board and pointing the way toward improved thermal control.

Another recurring plague of C/M photography is corona discharge which has been mitigated to some extent by a sophisticated array of rollers at anti-stat compounds but is far from solved. It is indicated that if the vehicle, and hence film, were maintained at an ambient pressure of 20μ to 100μ instead of at ambient this condition would be controlled. Work is in progress to develop such a light weight system, using perhaps freon or dry nitrogen and should be pressed with full support, and should be introduced along with a periodic pressure check.

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Further elaborate ground tests over a broader range of parameters for checking film flatness are suggested. These should include a broad temperature range and should be designed to test vibration and post acceleration effects.

Direct tests on film properties and sensitometry are discussed in Section III.

B. Engineering Passes with Daylight Photography of Design Aerial Targets. It is recommended that these be carried out with simultaneous recording of the data of the measurement program in A) above until one is driven to the conclusion that the system is working up to its design potential. The resulting loss of operational coverage due to such a program is both insignificant and a very worthy investment.

The design of aerial targets is investigated and one new conclusion calls for a three dimensional target casting a shadow, the the brightness of which provides a measure of contrast loss due to haze and of atmospheric scattering. In generall the target is desired to provide not only a measure of contrast reduction due to atmospheric scattering but also the transfer function from an edge measurement. For the loss of contrast due to haze, sensitometric exposures are desired - as proposed in Section III.

III. Film Processing and Sensitometry.

A. This is not the report but two questions must be discussed here.

a) How well do the mission parameters for slit width match with the processing curve for the cloud free regions?

b) Should a bigger range of slit widths be explored and is this an aircraft experiment?

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B. Both as a monitor of film uniformity and to provide a quantitative measure of contrast, or modulation, reduction due to haze, sensitometric strips are desired continuously along the film. There are pros and cons as to whether these strips are best introduced pre-flight, in-flight, or post-flight and pre-processing but no compelling reasons for the in-flight sensitometry emerged. It is felt that sensitometer stripping should be a standard procedure.

RECIPROCAL EDGE SPREAD MEASUREMENTS

Because of the fact that a great number of measurements of the apparent width of nominally sharp edges have been made and the intuitive feeling that these widths are related to the resolution, sharpness or acuteness of the pictures in which they appear, it would seem worthwhile to examine in a systematic way the relations and effects to be expected. The observer, looking through a microscope sees a region in which the intensity of the light transmitted by the negative grades from a low value in the more heavily exposed side of the edge to a higher value on the less exposed side. A typical plot of such an edge, freed of the effect of the ever present grain, is shown in Figure 1. Along a pair of lines parallel to the edge, there appears to be a transition from the edge itself to the uniform exposures on each side. The separation of these lines is the edge spread. The observer sets a cross wire along these lines in succession and measures their separation. He attempts to set the wire so as to separate the region of uniform intensity from the region where the intensity of the transmitted light is increasing or decreasing.

The first question to be answered is, "How is the decision made as to where to put the line?" Several pertinent attributes of the eye are known and understood. In the first place, the eye can detect a change in intensity across a sharp division of about 3%. In addition, it would appear that under favorable conditions of light intensity and adaptation, the eye is just able to detect an intensity gradient of 3% per minute of arc provided such a gradient extends for at least a minute of arc. While there are undoubtedly more subtle effects in the eye which should be considered, these will permit some understanding of the variables of the problem.

If we now plot the gradient required for detection of the presence of a gradient, as a function of the intensity, a curve something like Figure 2 will be obtained. Three regions of interest are shown. In the first region we know that at very low intensity, tending toward zero, a larger and larger gradient will be required for detection. In region 2 the 3% gradient as the threshold of detectability holds, while at very high intensities a saturation effect is bound to set in increasing the detectability limit.

Let us now return to Figure 1 and compute the slope as a function of displacement. In Figure 3, the distance coordinate x has been replaced by an angular coordinate θ, the angular subtence as seen by the eye. The relation between x and θ is determined by the magnification of the microscope. As one proceeds from left to right in the lower part of Figure 3, the value of $dB/d\theta$ increases to some value where the eye can detect it, point a for example. The location of this point will be determined from Figure 2 as the point a there as well. On the other side of the edge the intensity is higher and the first detectable gradient might well be higher also, as shown by point b in both Figure 2 and 3.

The magnification of the observing microscope determines the conversion from distance on the plate to angular distance as seen by the eye. It also determines the apparent brightness of the field. It can be shown that if the microscope is properly designed so that the exit pupil of the instrument coincides with the pupil of the eye, both in position and size, the eye will see a field of the same brightness as would be seen viewing the scene directly, except for

transmission losses in the optics. We will neglect such losses, although they could be of some importance and should be considered in a later discussion.

On the other hand, the apparent gradient in brightness is reduced by the magnification since two points of a given difference in transmitted intensity appear farther apart as the magnification is increased. The relation between the angular gradient as seen by the eye and the brightness gradient in the scene is

$$\frac{\Delta B}{\Delta \theta} = \frac{\ell}{M} \frac{\Delta B}{\Delta x},$$

where ℓ is the normal viewing distance, 10 inches, and M is the magnification of the microscope. We might well assume 100x. Then the first detectable logarithmic gradient is 90/rad and is equivalent to 3.55×10^{-2} per micron.

The actual spread of an edge, sharp in the scene, will be determined by the transfer function of the optical system and film, the exposure level on the two sides of the edge and the effective H&D curve. Let us assume that the processing is such that there is no Eberhard effect so that the H&D curve determined from large areas holds in detail across the edge to be measured. Since we shall be interested in small gradients, we shall try to fit the H&D curve with some analytic functions whose derivatives may be determined. Figure 4 shows a typical curve for the material in question. The equations giving good fit are

$$D = 0.1 + 0.96\ (\log E + 1.1)^3, \quad \log E \leq -0.2$$

$$D = 0.8 + 2.34\ (\log E + 0.2), \quad -0.2 \leq \log E \leq 0.1$$

$$D = 2.7 - 0.316\ (1.67 - \log E)^3, \quad 0.1 \leq \log E$$

Here E is the exposure in meter candle seconds and D is the density produced. The brightness B of the negative as viewed against a background of brightness B_o is

$$B = B_o \cdot 10^{-D}$$

The ~~gradient in~~ change B then is given by

$$\Delta B = 2.303\ B_o\ 10^{-D}\ \ D, \text{ and}$$

$$\frac{\Delta B}{B_o} = 2.88 \times 10^{-D}\ (\log E + 1.1)^2\ \frac{\Delta E}{E}, \quad \log E \leq -0.2,\ E \leq 0.63$$

$$\frac{\Delta B}{B_o} = 2.34 \times 10^{-D}\ \frac{\Delta E}{E}, \quad .02 \leq \log E \leq 0.1,\ 0.63 \leq E \leq 1.26$$

$$\frac{\Delta B}{B_o} = 0.948\ 10^{-D}\ (1.67 - \log E)^2\ \frac{\Delta E}{E}, \quad 0.1 \leq \log E,\ 1.26 \leq E$$

Because the material which has been measured was obtained under conditions where many effects were probably combined to yield the equipment transfer function, there seems no better assumption than to assume it to be Gaussian. The exposure of an edge will then be integral of the Gaussian curve. If

$$T(k) = e^{-2\pi^2 a^2 k^2}$$

then the variation of exposure of an edge separating a region of exposure E_1 from E_2 will be given by

$$E(x) = E_1 + (E_2 - E_1)\left[\frac{1}{\sqrt{\pi}} \int_0^{\frac{x}{a\sqrt{2}}} e^{-y^2}\, dy + \frac{1}{2}\right].$$

Thus

$$\frac{dE(x)}{dx} = (E_2 - E_1)\, \frac{1}{a\sqrt{2\pi}}\, e^{-\frac{x^2}{2a^2}} ,$$

which is the gradient of the exposure we seek. It is now possible to investigate the apparent edge spread for a group of typical cases. The process will be to assume that the edge spread will be measured between points which have a gradient of 3% per minute of arc. The exposure gradient will be computed for a number of cases by the first set of equations and from this the distance x will be found from the spread functions for various resolutions. Since the resolution variable leads to a smaller number of cases, it will be considered first.

The assumed Gaussian transfer function for the system may be slid along the resolution axis to represent systems in different states of perfection. The parametric variable is the high contrast three-bar target, limiting resolution. The detectability curve is obtained from REH-111, a Perkin-Elmer technical memorandum attached as Appendix 1. The position of the transfer function necessary to give the desired intersection yields the root mean square width of the line spread function a. Figure 5 shows the curves used. Table I shows the results.

Table I

Case	Limiting Resolution	RMS Spread, a
1	50 l/mm	0.0091 mm
2	70	.0056
3	100	.0039
4	120	.0029
5	150	.0021

The lower resolution cases are more doubtful than the ones of higher value because of the variability of the eye contrast threshold.

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The density difference across the edge and the mean density are variables of the problem. Table II illustrates the cases considered.

Table II

								$\frac{\Delta G}{\Delta x}$	
Case	D min	E min	D max	E max	$\bar{D}$	$\bar{E}$	ΔD	min	max
A	1.1	0.83	1.3	1.00	1.2	0.91	0.2	0.157	0.304
B	1.0	0.76	1.4	1.13	1.2	0.91	0.4	0.115	0.431
C	0.9	0.68	1.5	1.26	1.2	0.91	0.6	0.082	0.600
D	0.8	0.63	1.6	1.38	1.2	0.91	0.8	0.060	0.850
E	0.4	0.37	0.8	0.63	0.6	0.50	0.4	0.0254	0.060
F	0.1	0.30	0.5	0.44	0.3	0.30	0.4	0.0140	0.031
G	2.0	2.34	2.4	5.00	2.2	3.24	0.4	5.2	50.0

Conclusions: The results of the computations are shown in Figure 6. First, it would appear that the RES values predicted are somewhat smaller than those actually encountered in practice. There may be many reasons for this, but among those to be considered are the magnification of microscope and the fact that it may not be possible in practice for the observer to detect a gradient as small as 3% per minute of arc especially in the presence of grain. It has been assumed that the illumination level is sufficiently high to insure that all measurements are made on the linear part of the eye response curve. The results reported for the detection of a brightness difference between two large uniform areas may not apply directly to the case of the detection of the start of a gradually increasing gradient. All of these effects would influence the observer to measure the width of an edge as somewhat smaller than has been assumed in these computations and thus the RES results would be larger. Nevertheless, considerable information may be obtained from a study of the curves of Figure 6. The simple relationship between RES values and the limiting resolution of a three-bar target in lines per millimeter for a particular density difference and average density is quite impressively linear. The variation of the position of the line for different density differences is rather small and is an unexpected result. On the other hand, the RES measurement for an edge of given density difference appears to increase rather strongly as the average density is increased. These curves must go through a maximum at some high density but apparently the computations were not extended far enough to show this maximum. In spite of these encouraging results, it does not seem possible to deduce an equivalent limiting resolution for the optical system from RES measurements unless a good deal is known about the average density of the edge. The density difference across the edge appears to have a small enough effect to be negligible.

Recommendations: As a result of this study, I would suggest that several groups of edges be prepared on material similar to the original negative stock and processed in the same way.

1. Simulated Edges. These photographs of edges should be prepared in the laboratory by the use of opaque straight edges. The film could be previously fogged to give the desired D min. A series quite similar to the cases shown in Table II would provide considerable information.

2. Edges from Scenes. A scene of very high ground resolution containing both natural and cultural edges should be printed on original negative material using a variety of transfer functions. If projection printing is used to simulate the scale, the original positive could be measured to determine the actual values of E min, E max and $\bar{E}$. Care should be taken to determine the H&D curves with precision.

These two families of edge pictures could then be measured by the standard method and the results compared with the computed predictions.. Careful consideration must be given to this program since it is not obvious the results of the computations or the results expected from the measurements will materially assist in the interpretation of RES values unless additional information is available on such factors as haze and the precise H&D curve of the material.

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